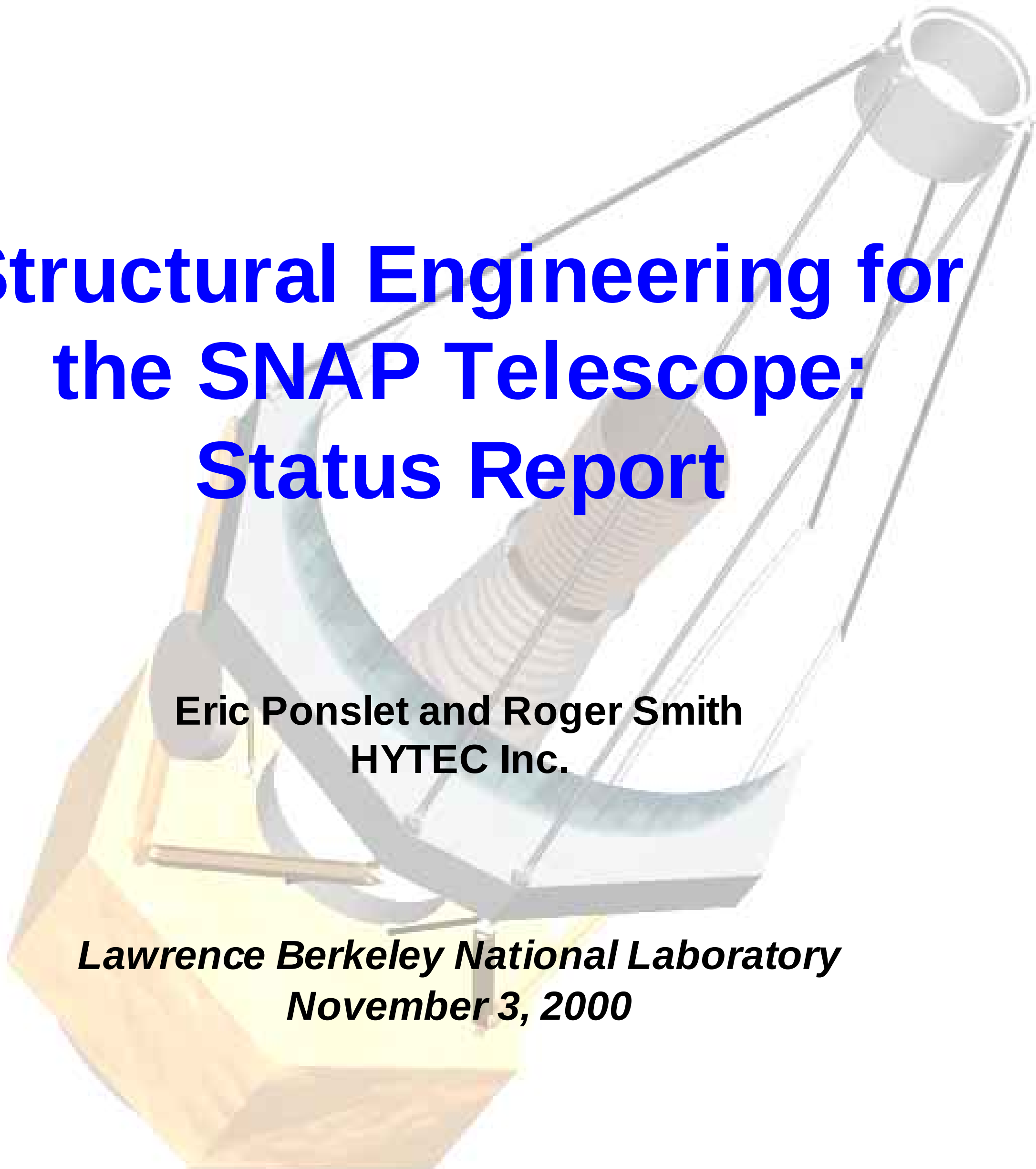
Structural Engineering for the SNAP Telescope: Status Report



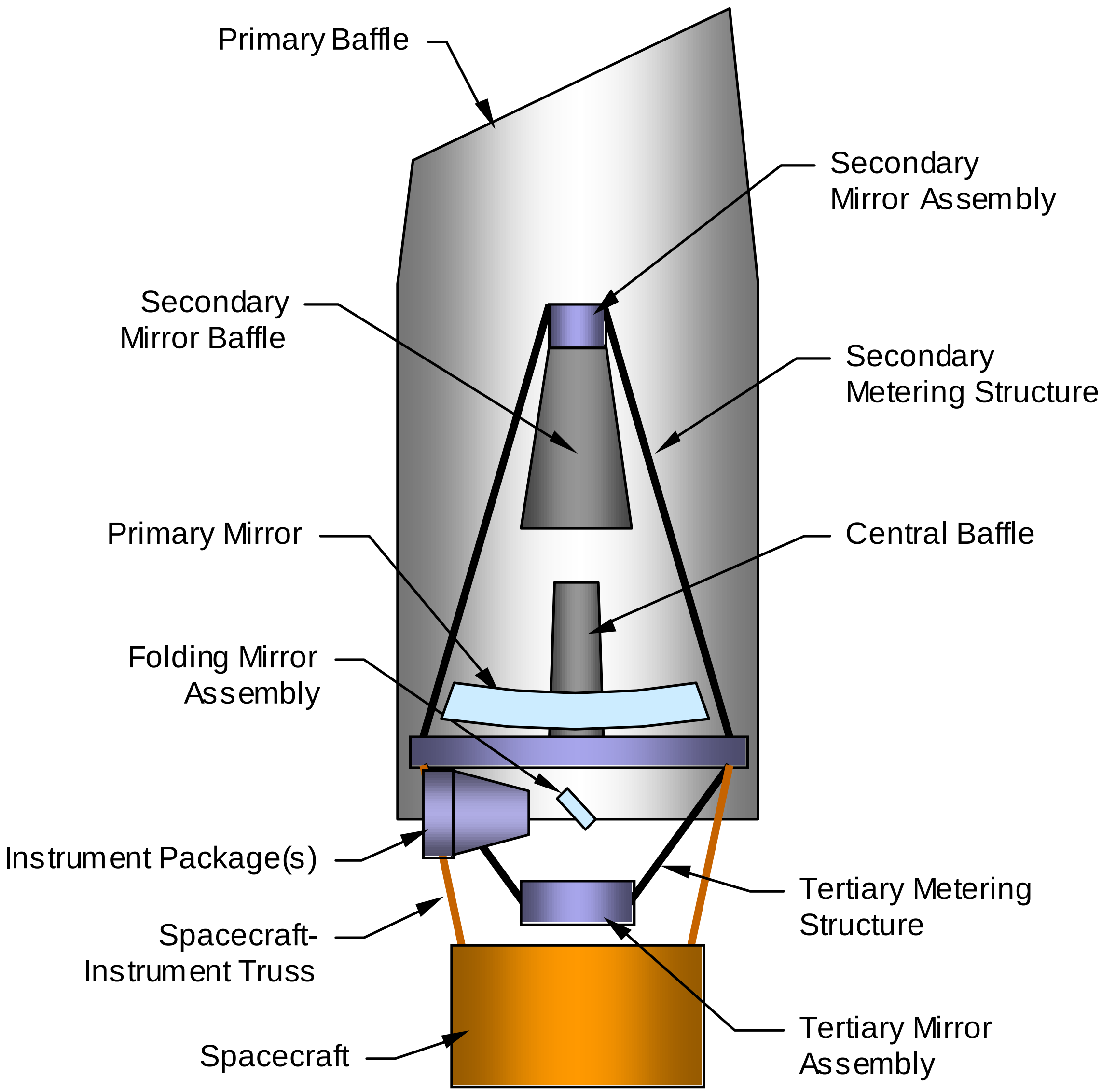
Eric Ponslet and Roger Smith
HYTEC Inc.

Lawrence Berkeley National Laboratory
November 3, 2000

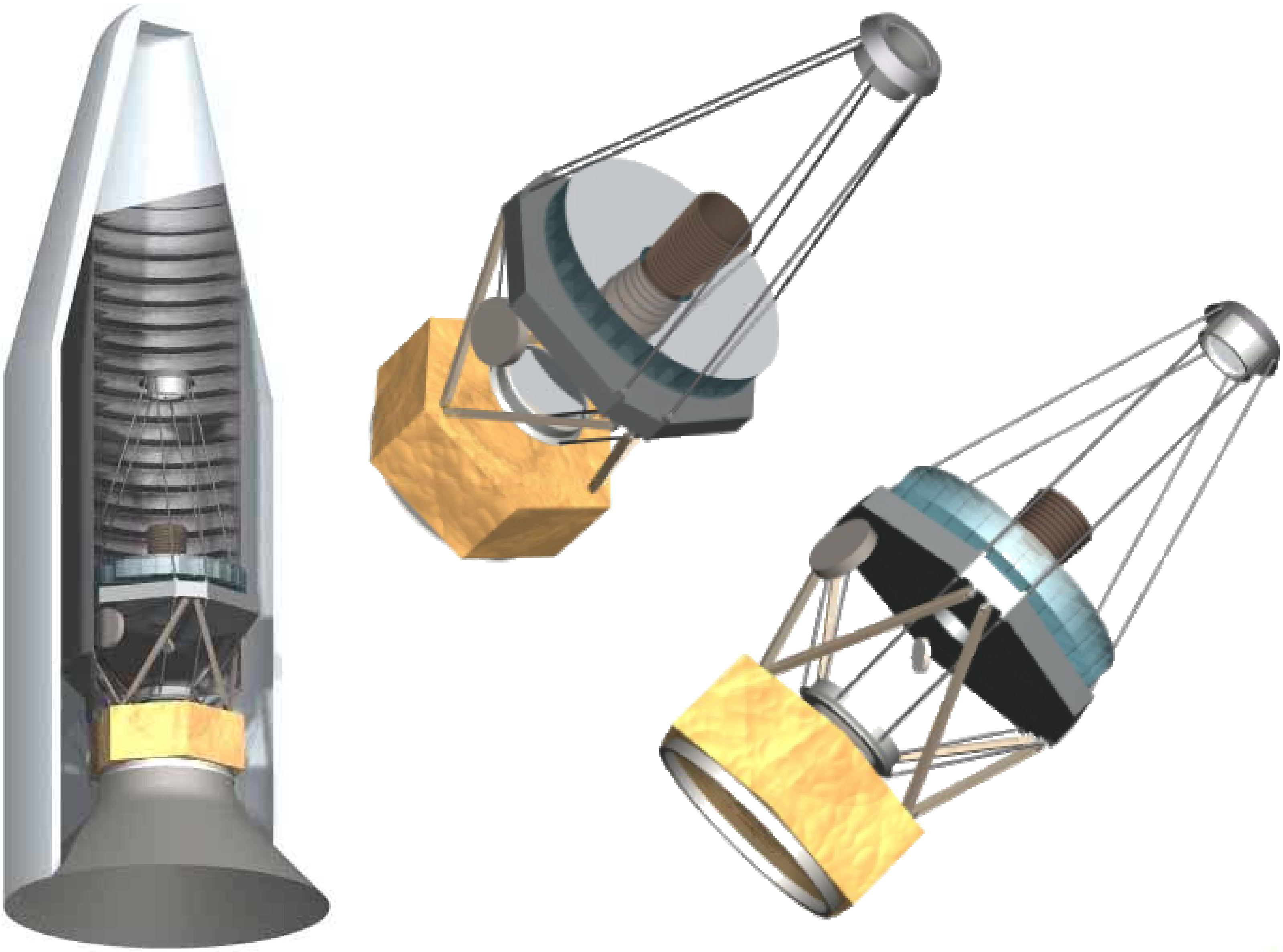
Outline

- Who is HYTEC? --- SECTION REMOVED ---
  - Experience with composites, space applications, and stable structures
- The SNAP Baseline Structural Concept
- HYTEC's Role in SNAP
  - Contractual commitments
  - Outline of progress
- Assumptions and Requirements for Initial Studies
- Summary of Conceptual Design and Analysis Work
  - Stable structure and material design
  - Secondary Metering Structure
  - Tertiary Metering Structure
  - Spacecraft-Instrument Interface Structure
  - Primary Mirror Substrate
  - Primary Optics Bench
  - Primary Baffle
- Conclusions and Special Issues Identified
- Future Work

SNAP Telescope - Current Structural Concept

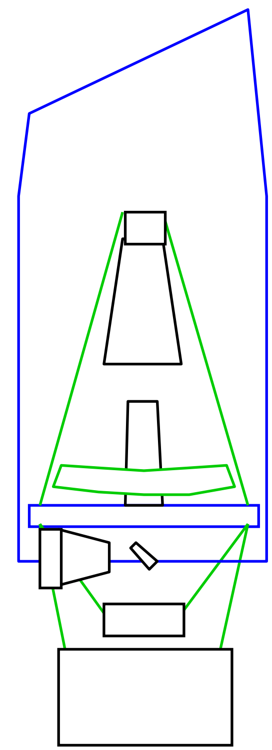


SNAP Telescope - Current Structural Concept



SNAP Structural Design Work at HYTEC

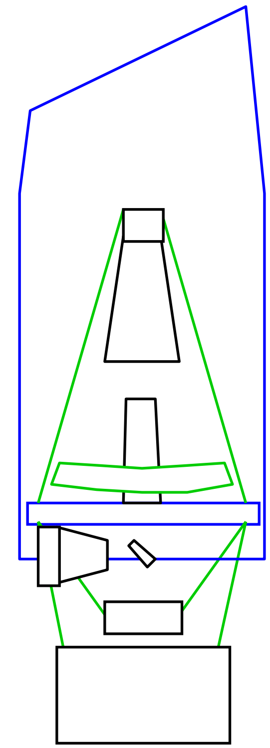
- HYTEC is under contract with LBNL to:
  - Establish baseline structural design requirements
  - Explore conceptual design options for all telescope structures
  - Perform preliminary analysis as required for initial sizing
  - Establish structural design baseline by February 2000
- May 2000 - present: 1 engineer + 1 part time CAD designer
  - Adding second engineer on November 7
- Progress to date:
  - Design requirement document was produced (1 document)
    - Identifies design issues
    - Lots of TBD's, documents *assumptions* made in design studies
  - Overall telescope layout in 3-D CAD models
  - Background research on stable optical telescopes
    - Literature about other projects and R&D efforts: telescope design, stable composites, stable structural design, etc…
  - Secondary Mirror Metering Structure (3 reports)
    - Conceptual design: direct/indirect support concepts, materials,…
    - Direct support frames and trusses
      - Sizing for dynamics, buckling, stresses
      - Obscuration and diffraction issues
      - Design trends



Conceptual design and preliminary sizing:
— Completed
— In progress
— Not started

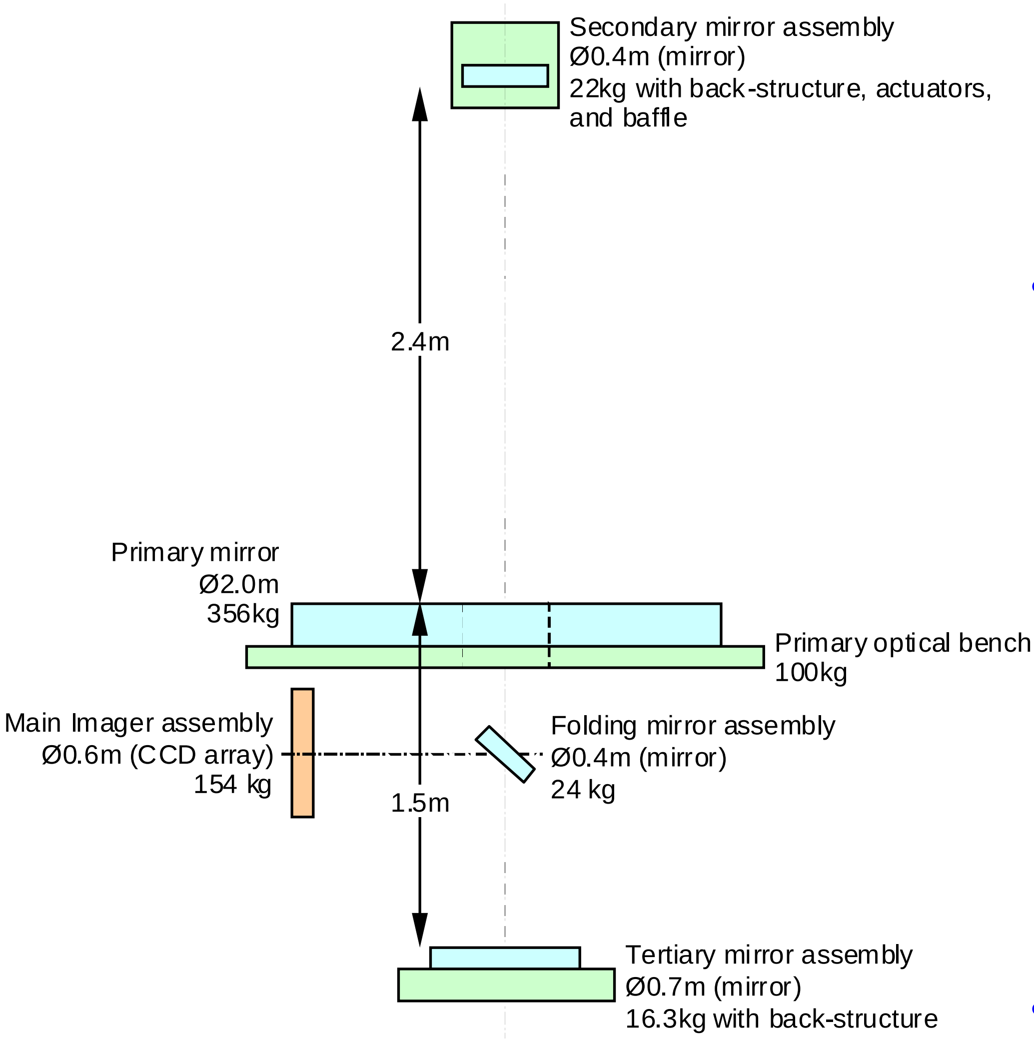
SNAP Structural Design Work at HYTEC

- Progress to date (continued):
  - Tertiary Mirror Metering Structure (1 report)
    - Easier design problem: no obscuration issues, smaller dimensions
    - Maximize use of designs/components common to Secondary support structure
  - Spacecraft – Instrument Interface Structure (1 report)
    - Kinematic mount for strain decoupling
    - Extreme stability *not* required
    - Sizing for dynamics, buckling, and stresses
  - Primary Mirror Substrate (report to be issued)
    - Definition of a conservative baseline design
    - Analysis of baseline design for dynamics, deflections, and stresses
    - Support conditions for 1g figuring and launch
  - Primary Optical Baffle (started)
    - Dynamic modes of stiffened shell
  - Primary Optics Bench (started)
    - Examine design options: single piece/multiple pieces, bench/ring approach, construction concept
    - Minimize axial space required (primary-folding distance)
    - Analysis for dynamics, deflections, and stresses



Conceptual design and preliminary sizing:
— Completed
— In progress
— Not started

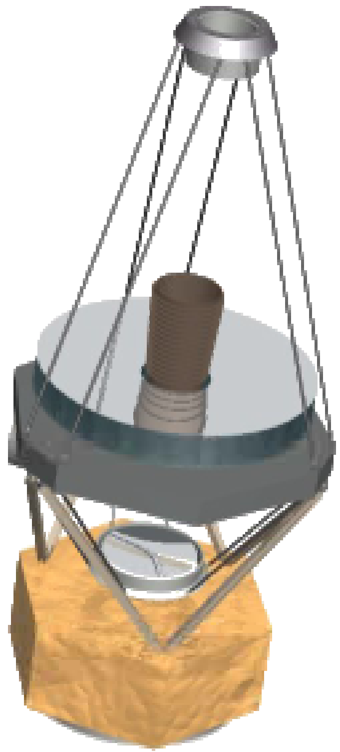
Assumptions and Key Requirements



- Dimensional Stability
  - Metering structures
  - Mirror assemblies
  - Primary optics bench
  - Instrument package(s)
- Launch Related
  - Baseline Vehicle: Delta IV-M
  - Payload Stiffness Requirements:
    - Fixed-base *spacecraft*:
      - $f_{transverse} > 10$ Hz
      - $f_{longitudinal} > 27$ Hz
    - Telescope sub-structures:
      - $f > 35$Hz
  - Pseudo-static design cases
    - 0.5g transv. + 6.5g long.
    - 2.0g transv. + 2.5g long.
  - Sine Vibrations
  - Acoustic loads
- Obscuration and diffraction
  - Goal: < 3.5% obscuration

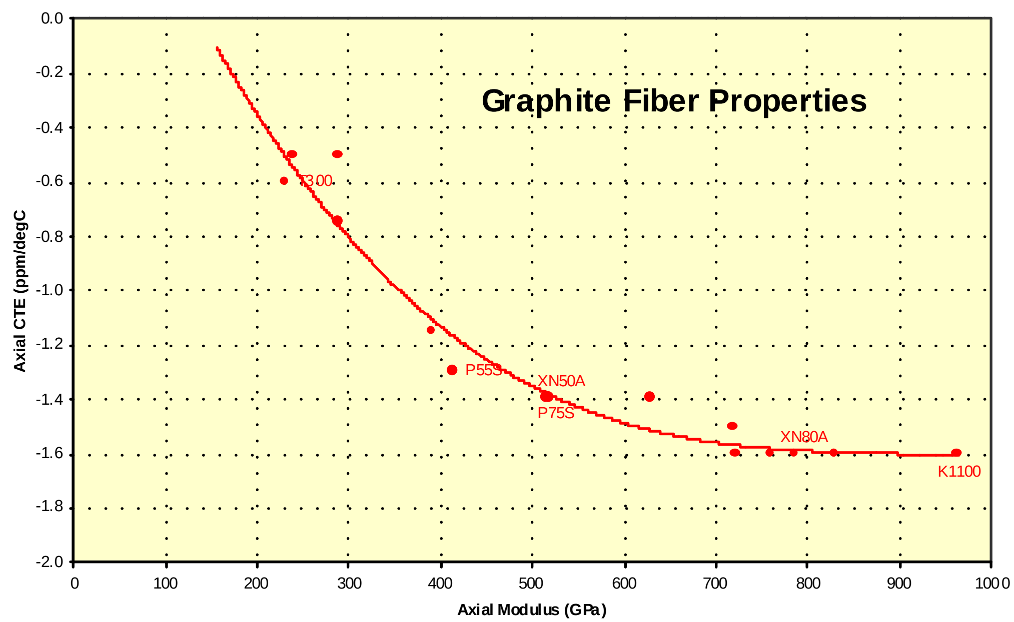
Designing for Dimensional Stability

- A few "rules" of stable structure design
  - Maintain as much symmetry as possible (including composite layups)
  - Keep load paths short, simple, and well defined
  - Use stable materials:
    - low CTE, low CME, coatings, low outgassing, no aging issues, etc…
  - In GFRP structures, design all critical joints to avoid relying on through-the thickness properties
  - Strive for strain-free structures and assemblies:
    - Kinematic interfaces
    - Favor trusses over frames
    - Minimize dissimilar materials
    - Room temperature cured adhesives
- Also, if required
  - Minimize temperature gradients and fluctuations:
    - High thermal conductivity
    - Shielding
    - Active control (heaters,…)
    - Orbit design
  - Minimize sources of dynamic disturbances
    - Vibration isolation of noise sources

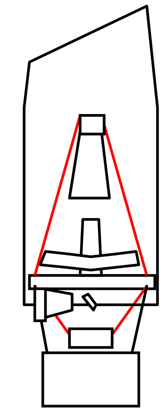


Dimensionally Stable GFRP Composite Materials

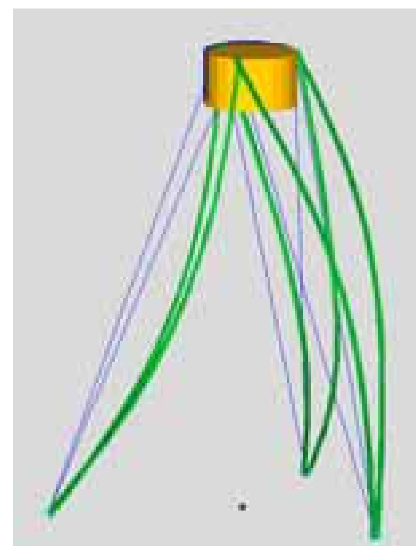
- Graphite Fiber Reinforced Plastics
  - High modulus graphite fibers (negative CTE)
  - Thermoset resin matrix (positive CTE)
    - Select low moisture expansion (CME and saturation) resins (cyanate esters)
    - Metal coatings slow absorption/desorption rates
  - Low stress allowable to avoid permanent deformations from launch (microyield)
- Tailorable properties
  - CTE “tuned” through fiber/matrix selection, fiber volume content, and layup design
  - Variability in processing leads to somewhat variable properties
    - Development must include thorough testing program



Metering Trusses - Design Aspects



- Strut design
  - Stiffness driven designs
    - Buckling and stresses never found critical
  - Minimize cross sectional dimensions (obscuration)
  - Violin modes dominate dynamic response
    - Tubular composite struts have highest violin frequencies
    - Violin frequency function of material, length, and *diameter* only (*not* wall thickness)
    - Pinned ends violin mode frequencies are 2.25 times lower than built in ends…
  - End fittings
    - Bonded to tube ends
    - Low CTE materials
      - Titanium, Invar, composite
    - Provide pinned end conditions (flexures) to avoid initial strains
    - Lock flexures after alignment to increase violin frequencies?
      - Potting, bonded sleeve



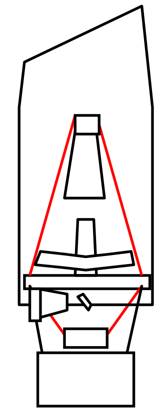
Typical violin mode of a support truss

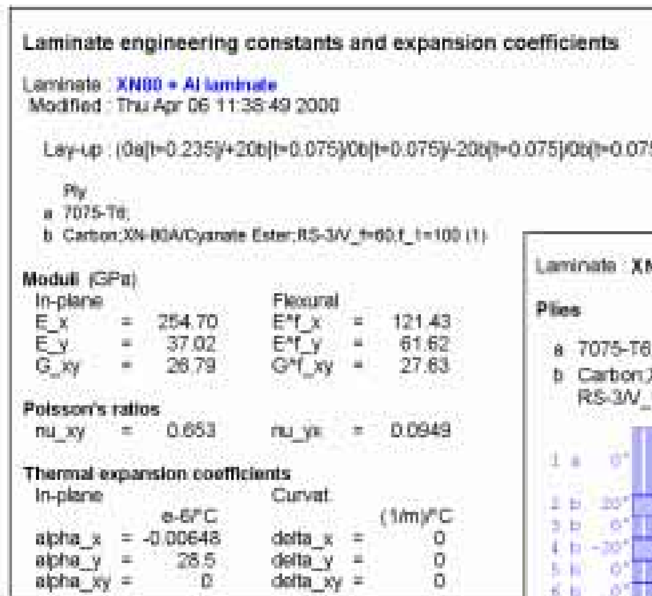
Metering Trusses - Materials

- Material design compromise:
  - High longitudinal modulus
  - Near zero longitudinal CTE

  } Competing requirements

  - Typical "zero-CTE" GFRP:
    - 75 Msi fiber (P75, XN50, M55J), about 60% fiber volume content
    - Quasi Isotropic $(0/-45/45/90|_{ns})$
    - CTE~0, E~100 GPa
  - Assumed material:
    - 250 GPa, 2220 kg/m^3
    - Easily achieved with high modulus fibers and custom layup
      - CTE ~ -1×10^{-6}/ºC
      - Density ~ 1800kg/m^3
  - Material development?
    - Hybrid layup of high modulus GFRP layers and high CTE metal layers
    - 250 GPa, 0 CTE, 2200 kg/m^3 feasible on paper
    - Manufacturing and thermal cycling issues





Laminate engineering constants and expansion coefficients

Laminate : XN80 + Al laminate
Modified : Thu Apr 06 11:38:49 2000

Lay-up : (0a|t=0.235)/+20b|t=0.075)/0b|t=0.075)/-20b|t=0.075|/0b(t=0.075

Ply
a 7075-T6;
b Carbon:XN-80A/Cyanate Ester:RS-3/V_f=60,t_1=100 (1)

Moduli (GPa)

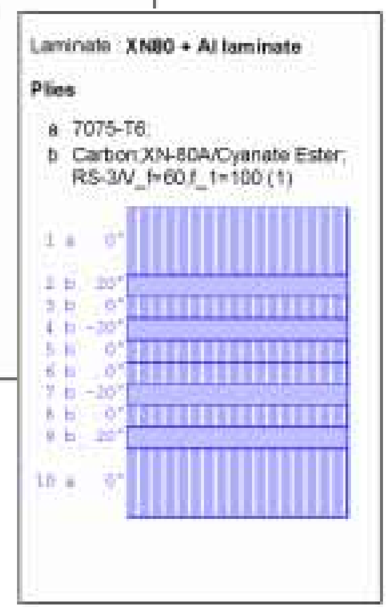
In-plane			Flexural		
E_x	=	254.70	E*f_x	=	121.43
E_y	=	37.02	E*f_y	=	61.62
G_xy	=	26.79	G*f_xy	=	27.63

Poisson's ratios

nu_xy	=	0.653	nu_yx	=	0.0949

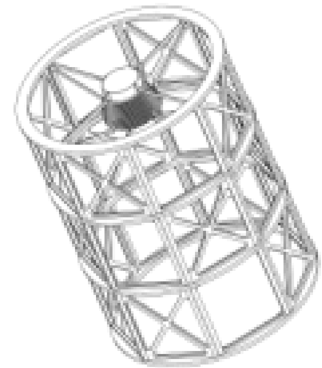
Thermal expansion coefficients

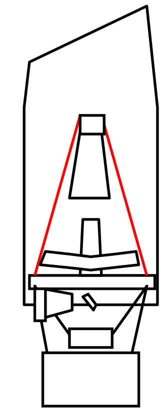
In-plane		e-6/°C	Curvat.		(1/m)/°C
alpha_x	=	-0.00648	delta_x	=	0
alpha_y	=	28.5	delta_y	=	0
alpha_xy	=	0	delta_xy	=	0



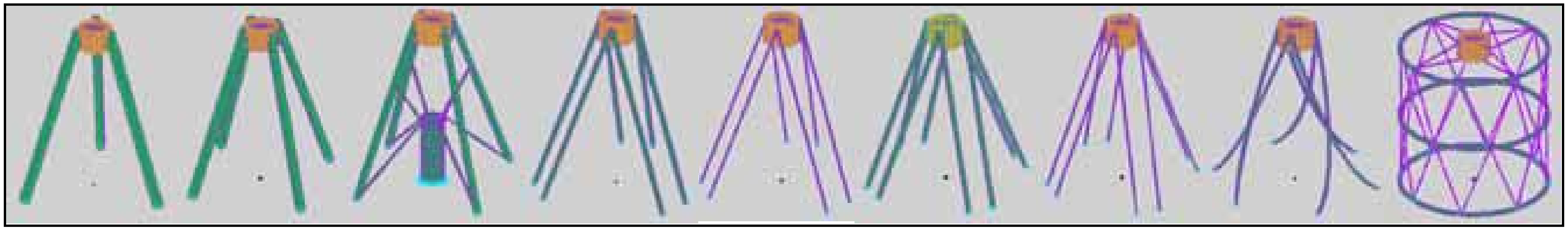
Secondary Metering Structure

- Key requirements:
  - Minimize obscuration (<3.5%) & interference spikes
  - Dimensional stability
  - 35 Hz minimum fundamental frequency
- Conceptual design options:
  - Indirect support:
    - Large structure outside of aperture + short radial spider
    - Higher mass and complexity, lower modularity
    - Higher stiffness, lower obscuration
  - Direct support:
    - Entire support structure sits in aperture
    - Lower mass, simplicity, modularity
    - Difficult obscuration / stiffness compromises
  - Cross-braced direct support:
    - Attempts to increase stiffness with cross-bracing
    - Cross bracing in “shadow” of primary struts
  - Trusses VS Frames
    - Frames rely on bending stiffness of beams
      - Require larger cross sections
      - sensitive to bending deformations in struts (thermal)
      - usually not kinematic

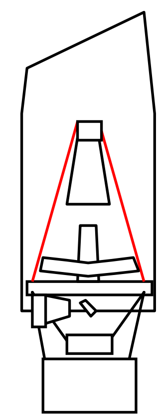




Secondary Metering Structure

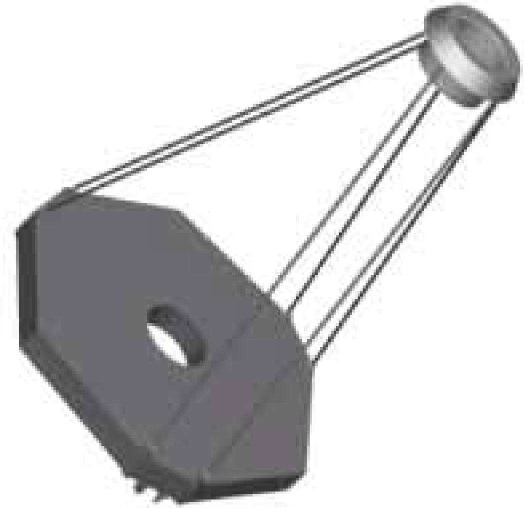


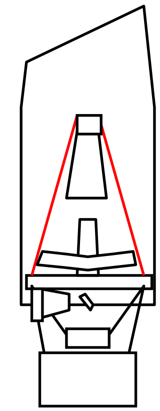
	Tripod	Quadrupod	Cross-Braced Quadrupod	Hexapod truss with pinned ends	Hexapod truss with fixed ends	Octopod truss with pinned ends	Octopod truss with fixed ends	Curved leg hexapod	Hubble style (indirect support)	
# legs	3	4	4	6	6	8	8	6	4	ea
outside diameter	112	102	67	48	23	48	24	38	18	mm
wall thickness	1.0	1.0	1.0	1.0	1.0	1.0	1.5	1.0	1.0	mm
obscuration	8.6	10.4	6.8	7.3	3.5	9.8	4.9	8.2	1.8	%
interference spikes	6	4	4	4	6	4	4	0	4	ea
lowest violin mode	197	180	?	36	35	36	35	59	84	Hz
lowest global mode	35	35	34	56	35	?	39	35	35	Hz
mass of composite	6.4	7.7	8.9	5.5	2.6	7.3	5.2	4.5	12.1	kg
mass of fittings	39.7	41.3	16.1	8.5	1.4	11.3	1.8	4.6	10.1	kg
total mass of metering structure	46.1	49.0	25.0	14.0	4.0	18.6	7.0	9.1	22.2	kg

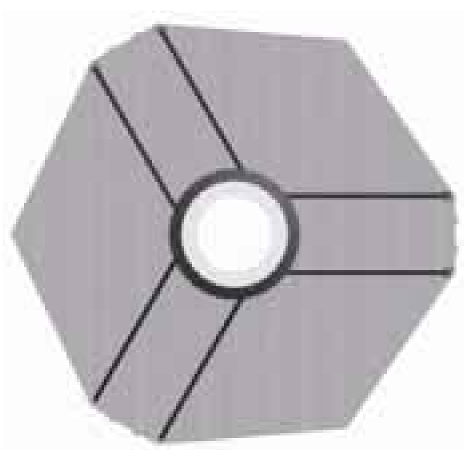


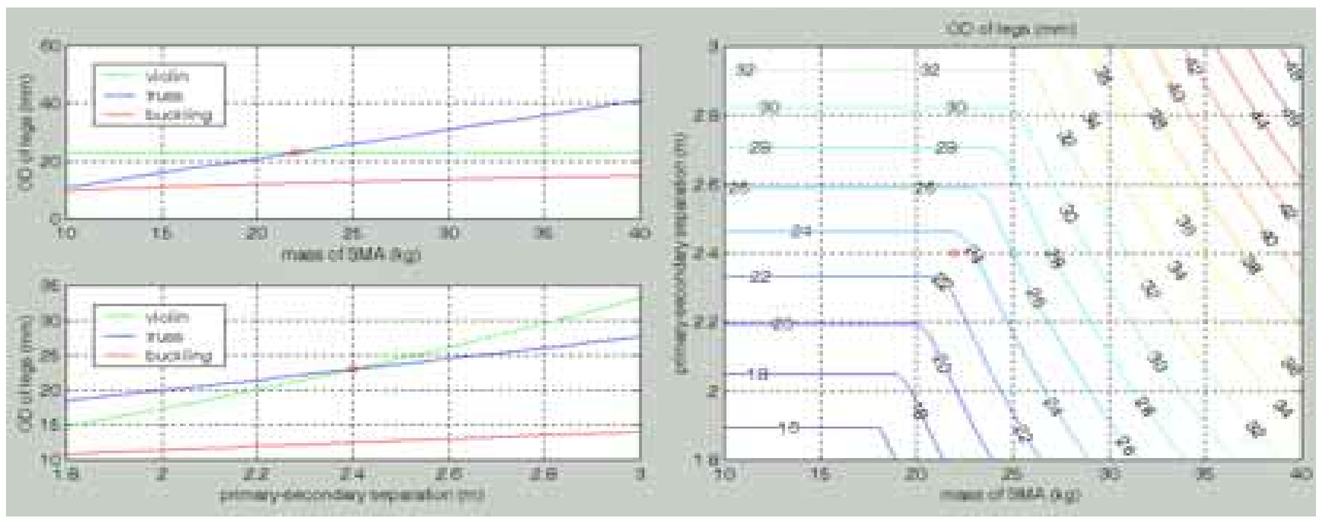
Secondary Metering Structure

- Baseline design: hexapod truss with fixed end
  - Simple design with low obscuration (3.5%)
  - 6-spiked diffraction pattern
  - Ø 23 mm by 1 mm wall tubular composite (250 GF material) struts with invar end-fittings.
  - “Optimal”: both violin and truss modes are critical No stress or buckling concerns
  - Requires locking of end flexure after initial alignment (violin modes)
  - Total mass ~ 4 kg





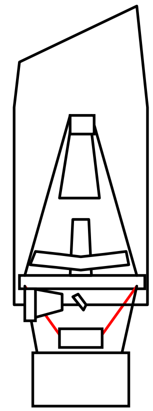


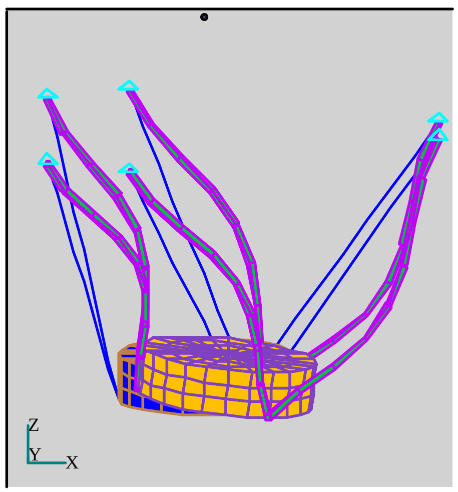


Design trends for fixed-end hexapod truss as a function of SMA mass and primary-secondary separation

Tertiary Metering Structure

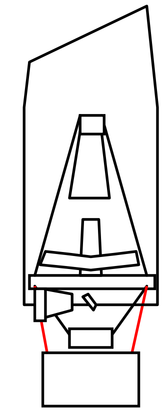
- Key requirements:
  - Dimensional stability
  - 35 Hz minimum fundamental frequency
- Easier design problem than secondary metering structure
  - Overall dimensions much smaller than secondary metering truss
  - No obscuration concerns
  - Use strut design from secondary metering structure (cost effective)
- Baseline design
  - Ø 23 mm by 1 mm wall composite tubes
  - Invar end fittings
  - Total mass ~ 3 kg
  - Fundamental mode = violin mode @ 58 Hz
  - No stress or buckling concerns



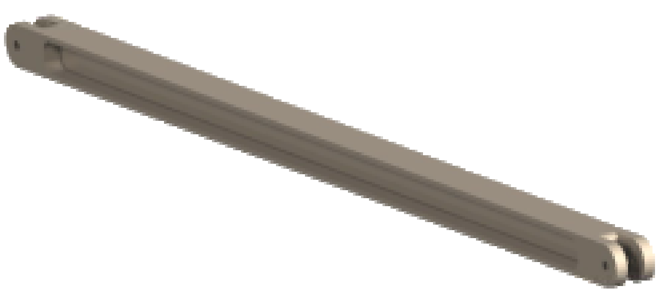


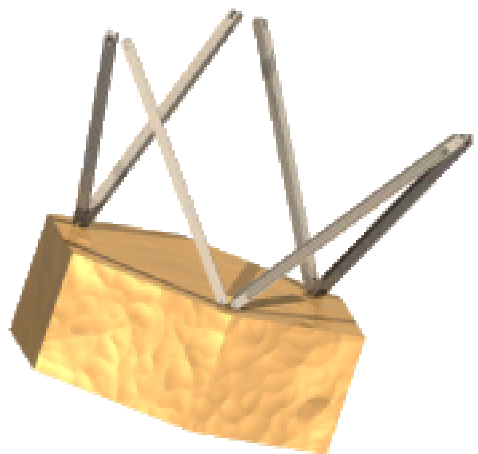
Lowest global mode of tertiary metering truss: 110Hz

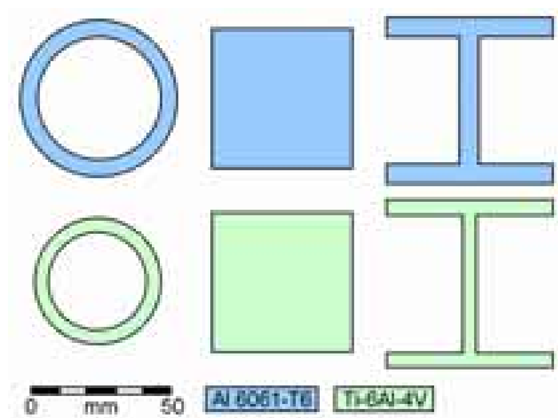
Spacecraft - Instrument Interface



- Key requirements and issues:
  - Kinematic interface (spacecraft bus not dimensionally stable)
  - High stiffness
    - Require frequencies >14 Hz transverse and >38 Hz axial for fixed base interface (2x requirement for fixed base spacecraft)
  - Strength and buckling safety
- Stability not a real issue → conventional materials (Ti or Al alloys)
- Baseline design
  - Kinematic truss (6 struts) with pinned ends
  - Both violin (38 Hz) and truss (17 Hz) modes near critical
  - Overall stresses are low (SF from 13 to 75)
  - Buckling near critical (SF from 2 to 7)
  - Total mass ~ 37 kg



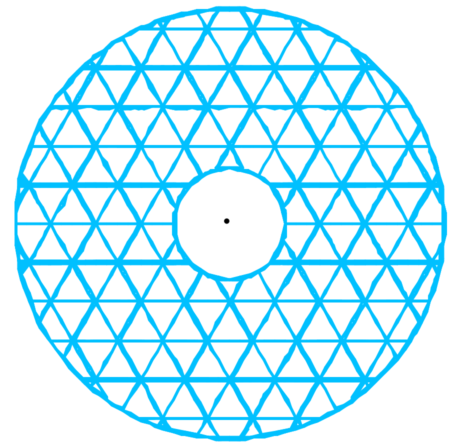


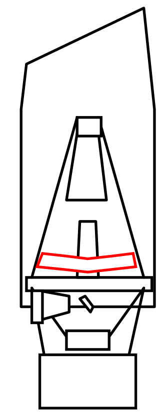


Minimum cross sections of spacecraft-instrument struts

Primary Mirror Substrate

- Key requirements and issues
  - Dimensional stability
  - High specific stiffness (1g sag, acoustic response)
  - Stresses during launch
  - Design of supports
- Baseline technology
  - Multi-piece, fusion bonded, with egg-crate core
  - Meniscus shaped
  - Triangular core cells
    - Maintains 0/120/240 symmetry of the entire telescope
    - Little performance difference with other common cell geometries (hexagonal, square)

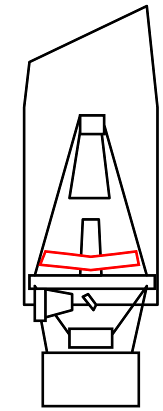


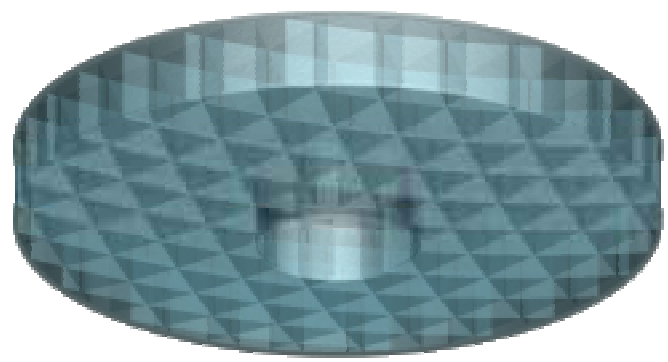


- Material
  - Baseline = ULE Glass (Corning)
    - Worst case: other materials such as Zerodur (Schott) have higher *E/ρ*
  - Allowable stress (macroscopic) must be conservatively low
    - Brittle material, lots of pre-existing defects (cracks) at the bonds
    - Design allowable = 600 psi / 4.1 MPa

Primary Mirror Substrate

Finished Dimensions				
outer diameter	2.000			m
center hole diameter	0.500			m
total thickness	0.250			m
top face thickness	0.015			m
bottom face thickness	0.015			m
outer band thickness	0.006			m
inner band thickness	0.006			m
web grid	square	triangular	hexagonal	
web spacing (inscribed circle diameter)	0.120	0.120	0.120	m
web thickness	0.005	0.005	0.005	m
unit cell area	1.4E-02	1.9E-02	1.2E-02	m^2
alpha	4.2E-02	4.2E-02	4.2E-02	
core solid fraction	0.082	0.082	0.082	
approximate number of cells	205	157	236	
core thickness	0.220			m
core solid fraction	0.082			
Masses				
top face	97			kg
bottom face	97			kg
core	116	116	116	kg
inner band	5			kg
outer band	18			kg
TOTAL	**334**			**kg**
lightweighting	**79**			**%**
mass per unit area	113			kg/m^2
Natural Frequency Upper Bound (free-free)				
centerline face separation (h)	0.2350			m
bot. centerline to bending axis (b)	0.1175			m
bending stiffness equiv. (Et3/12)	2.80E+07			Nm
aspect ratio (ID/OD)	0.25			
free-free eigenvalue^2 (no shear)	5.01	8.39		
free-free fund. mode (no shear)	**403**	**675**		**Hz**
Natural Frequency Upper Bound (simply supported OD)				
free-free eigenvalue^2 (no shear)	4.69	13.20		
free-free fund. mode (no shear)	**377**	**1062**		**Hz**
1g Vertical Axis Face Ripple Approximation				
P-P ripple (circular plate, no shear)	**1.47E-08**			**meter**

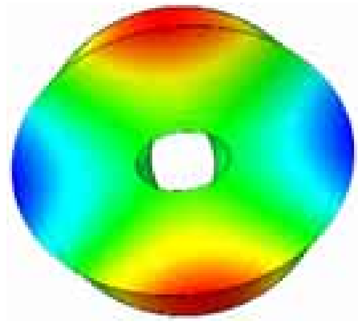




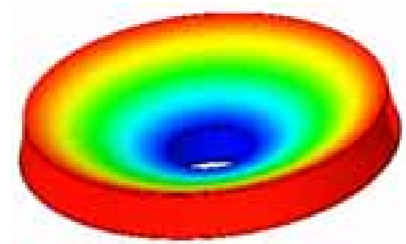
Initial design for primary mirror substrate: 334 kg

Primary Mirror Substrate

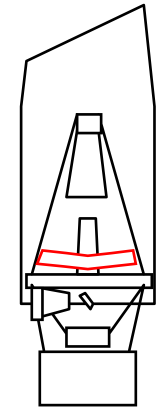
- Free-free modes



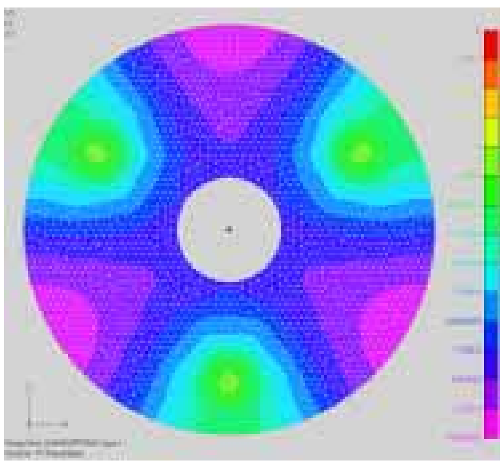
Fundamental mode: 360 Hz



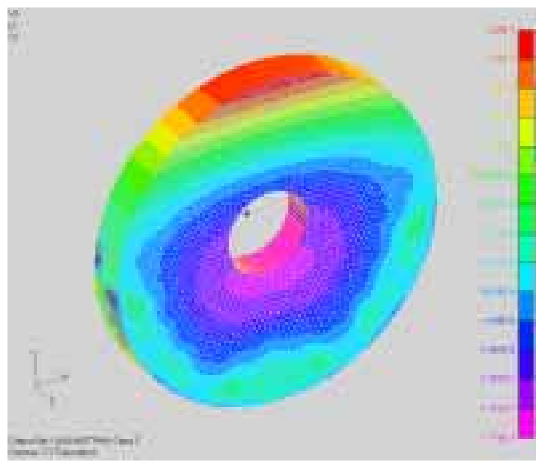
Second mode: 566 Hz



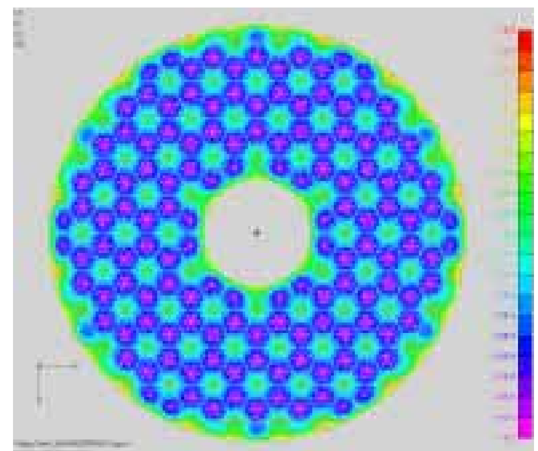
- Sag during 1g figuring
  - Sag is too large (>0.1µm) on simple supports (3 pt vertical, strap horizontal)
  - Will likely require vertical axis figuring on airbag supports



1g sag on 3pt support
vertical axis
P-P Z deflection = 2.3 µm

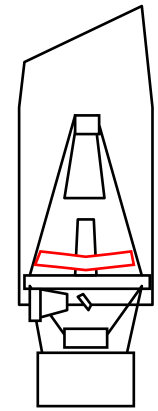


1g sag in 180º strap support
horizontal axis
P-P Z deflection = 0.5 µm

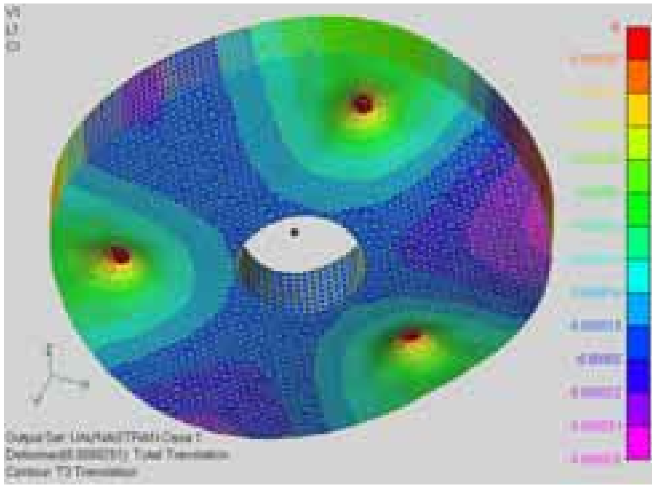


1g front face ripple on perfect
back-side support
P-P Z deflection = 0.018 µm

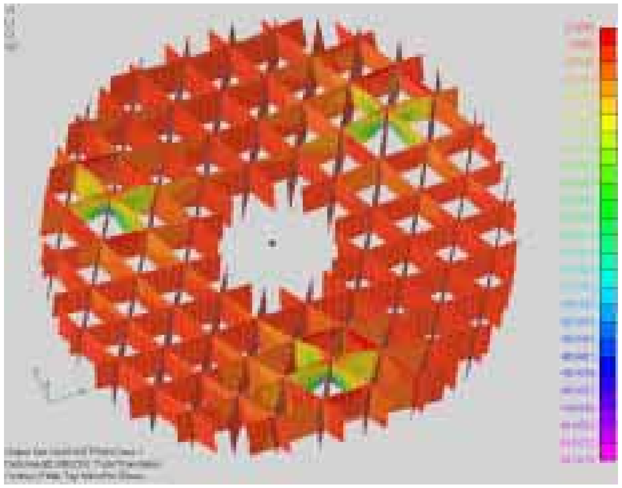
Primary Mirror Substrate



- Stresses from pseudo-static launch load factors
  - 6.5g axial, 0.5g transverse
  - 3-point supports with Ø 6cm ×2 cm thick Invar pads
  - Stresses are locally high: 5.5 MPa peaks (35% above allowable)



Mirror deformations under pseudo-static launch loads: peak deflection = 25 µm

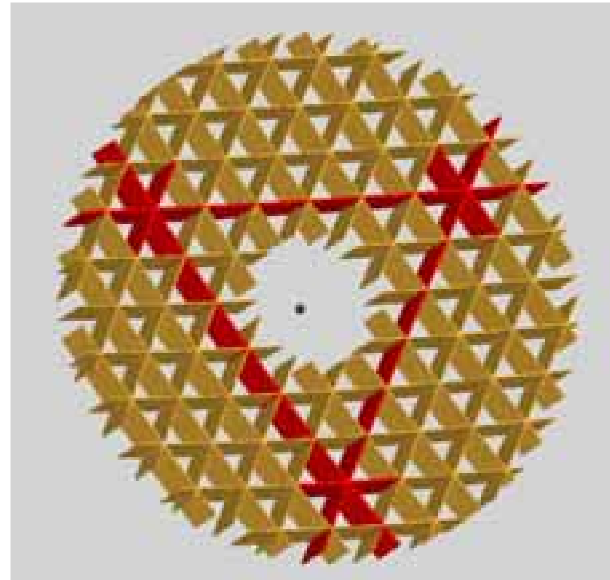


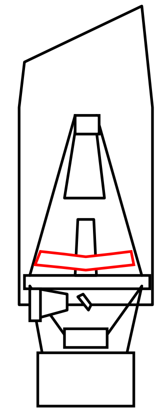
Stresses in mirror under pseudo-static launch loads: peak stress = 5.5 MPa (compressive)

- Lessons learned
  - Initial mirror design nearly acceptable
  - Advanced mirror support required for figuring
  - Conceivable that mirror could survive launch on simple 3 point kinematic support

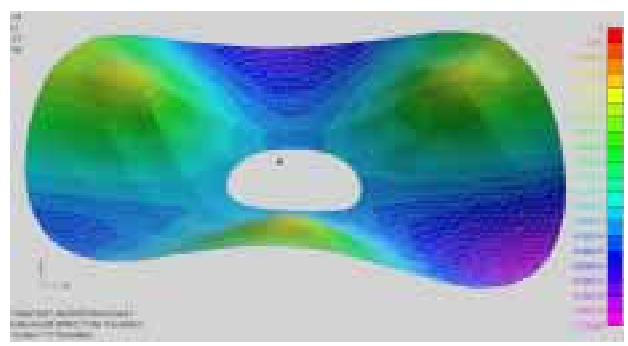
Primary Mirror Substrate

- "Improved" baseline
  - Thinner face sheets (12 mm)
  - Locally thickened web walls (10 mm)
  - Thicker outer ring (8 mm)
- Mass is unchanged (320 kg)
- Fundamental mode drops to 333 Hz
- Pseudo-static launch case
  - Stresses down to < 3.1 MPa
  - Deflections < 20 μm
- Conclusions
  - 80% lightweighted design is workable
  - 3 pt support *may* be usable for launch
  - Vertical axis airbag support required for figuring
  - More aggressive lightweighting would have little positive effect:
    - Stresses and deflections unchanged (1st order)
    - Increases technological risk?
    - Reduces instrument mass…



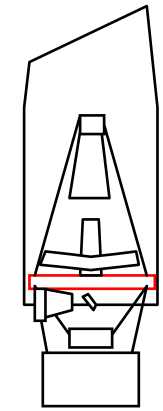


Modified design with locally thicker web plates
Standard web thickness = 5 mm (orange)
Thickened plates = 10 mm (red)

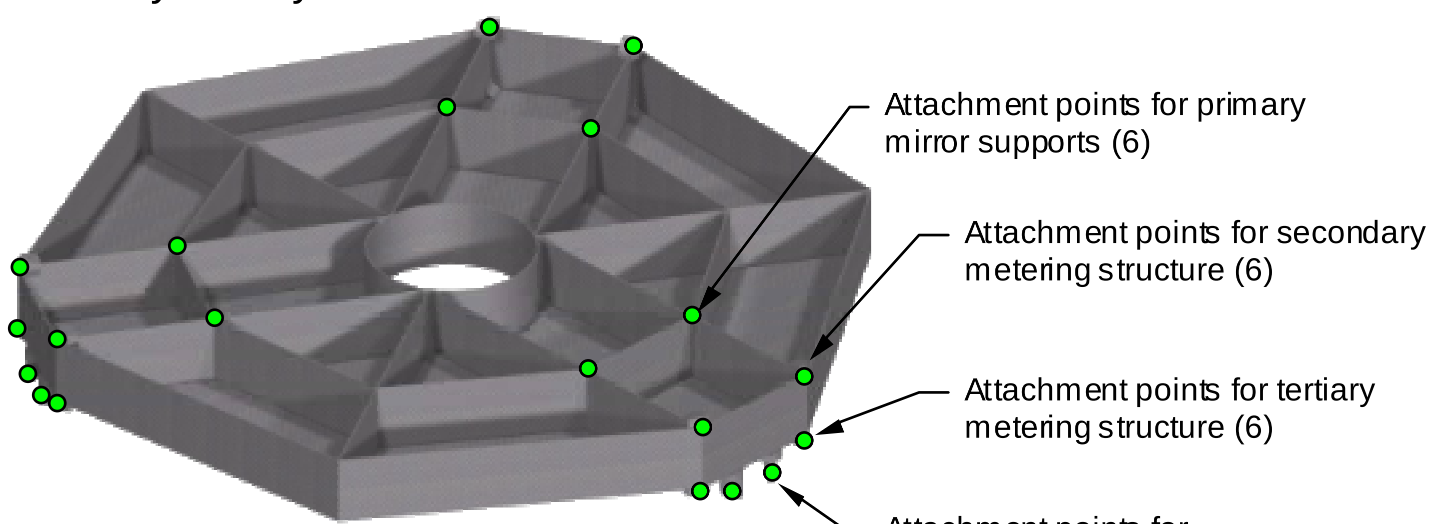


Deformations of mirror top face under pseudo-static launch loads: peak deflection = 20 μm

Primary Optics Bench

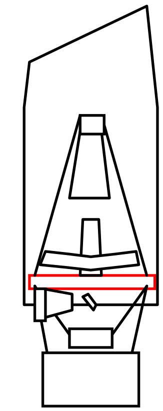


- Key requirements and issues
  - Dimensional stability
  - Stresses (supports 600 to 900 kg of instruments and mirror)
  - High stiffness
- Baseline technology
  - Bonded eggcrate construction from flat laminates (cost effective)
  - Invar fittings bonded to web plates for all interfaces
  - Attachment points for secondary and tertiary metering trusses, spacecraft interface, and primary mirror close to one another (short and direct load paths)
  - 0/120/240 symmetry

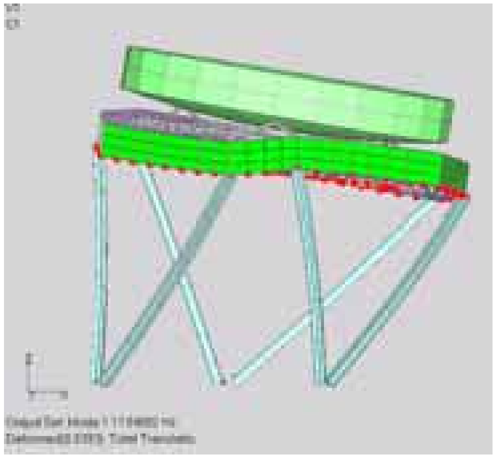


Structural concept for Primary Optics Bench
(top face removed)

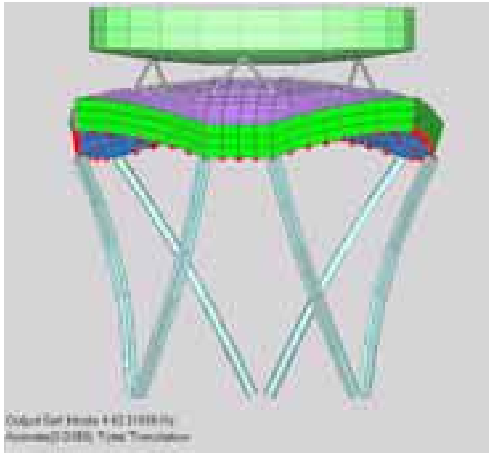
Primary Optics Bench



- Baseline material
  - 75 Msi fiber (P75, XN50, M55J), about 60% fiber volume content
  - Quasi-isotropic, symmetric, balanced layups, 4 mm thick
  - E ~ 100 GPa typical, near-zero CTE, ultimate strength ~ 275 MPa
  - μyield stress ~ 1/3 strength? Allowable for initial design ~ 75 MPa
- Just started simulations of initial design
  - 20 cm total thickness, 90 kg total structural mass
  - Assuming 540 kg (too much?..) of instruments distributed on bottom face, in addition to 320 kg mirror attached to top
  - Vibration modes rigid enough but show significant deformations of the POB itself

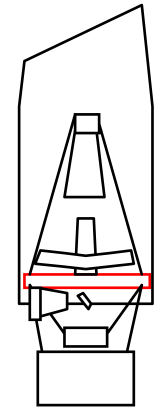


Fundamental mode of primary optics bench on interface truss: 17 Hz

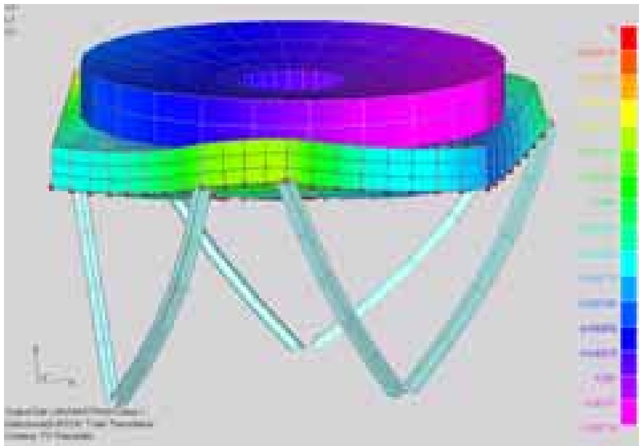


Third mode of primary optics bench on interface truss: 43 Hz

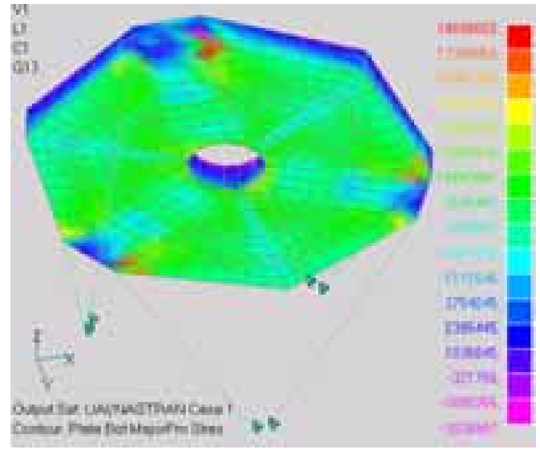
Primary Optics Bench



- Stresses under pseudo-static launch case
  - Deflections ~ 1mm
  - Stresses are acceptable: peaks near 30 MPa



Deflections under pseudo-static launch case 1: peak Z deflection = 1.14 mm

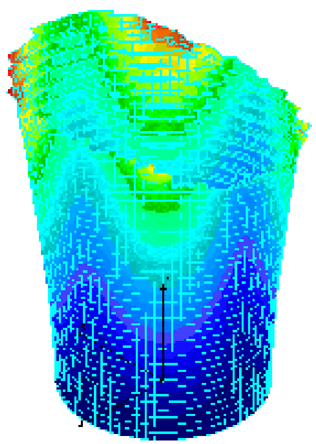


Average stresses from pseudo-static launch case 1: maximum stress ~ 30 MPa

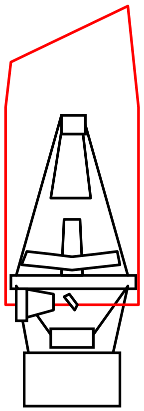
- Lessons learned and issues
  - Initial design is acceptable
    - Stresses at least a factor of 3 below conservative allowable
    - Stiffness is sufficient but marginal (longitudinal mode)
  - 20 cm total thickness is about right
  - Many other concepts to examine (ring shaped, honeycomb,…)
  - Large unsupported spans of face plate, attachment points for instruments,…

Primary Baffle

- Key requirement and issues
  - Stiffness
  - Optical properties of inner surface
  - Dimensional stability requirement?
  - Thermal conductivity
- Baseline design
  - Based on early layout, smaller than current design
  - Stiffened aluminum shell (HST)
  - Use baffle rings as stiffeners
  - 1 to 1.5 mm wall, about 125 kg (smaller design)



Fundamental mode of fixed-base baffle: 56 Hz



Conclusions and Critical Issues

- Summary of baseline designs examined so far:

	Materials	Mass (kg)	comments and special issues
Primary mirror	ULE Glass + Invar supports	320 + supports	• conservative design, 80% mass relieved. • three point support may be acceptable for launch. • need attention to support pad design. • will require vertical axis figuring on distributed support (airbag).
Primary Optics bench	M55J/CyE QI GFRP + Invar fittings	90 + fittings	• single point design analyzed so far. • egg-crate sandwich construction from flat laminates. • required thickness around 20 cm. • relatively high stresses, joint design require attention, protyping and testing. • will require carefull material development program. • many more concepts to examine...
Primary baffle	Aluminum alloy	125 + fittings	• fairly straightforward design if baffle rings can serve as stiffeners. • Aluminum alloy sheet metal construction (dimensional stability requirement?). • Structural interface to spacecraft?
Secondary Metering Structure	250GPa^{+}, "zero" CTE tailored GFRP + invar fittings	4	• obscuration and diffraction requirements are difficult to meet. • will require high-end materials and a careful material development program (high modulus, zero CTE, or both?). • strut end fittings: flexures for strain free assembly and alignment, but built in end conditions to raise natural frequency… needs attention (feasibility).
Tertiary Metering Structure	250GPa^{+}, "zero" CTE tailored GFRP + invar fittings	3	• fairly straightforward design as compared to secondary metering structure. • most cost-effective approach is to use strut design from secondary metering structure
Spacecraft-Instrument Interface	Aluminum alloy	35	• conventional materials are acceptable and lower risk and cost • end fitting design requires attention to insure pure kinematic joints

Future Work

- Finish first round of analytical design studies: define complete baseline
  - Primary optics bench
    - Several other concepts to examine
  - Primary baffle & support scheme
  - Instrument package(s)
  - Central baffle
  - Secondary Mirror assembly and baffle
  - Tertiary Mirror assembly
- Perform simulations of entire instrument
  - Modal analysis
  - Jitter from reaction wheels / damping requirements for metering trusses
  - Pseudo-static loading
  - First cut of dimensional stability simulations
- Establish work plan for development work
  - Include *early* efforts in material development, prototyping, and testing
    - Flat GFRP laminates
    - Near-zero CTE, ultra-high modulus GFRP tubes
    - End fittings
  - Thermal design aspects
  - Coordinate with mirror manufacturer (support conditions)